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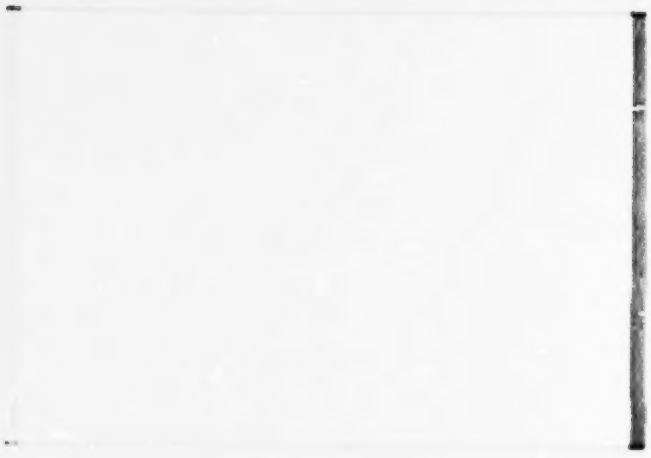

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SHELTER ENGINEERING LTD.

DRAFT PROCEDURES

FOR

THERMAL PERFORMANCE TESTING OF HOUSES

Prepared for:

The Technical Research Council

of

Canada Mortgage and Housing Corporation

and

The CSA Sub-committee

on

Test and Inspection Methods

by

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DRAFT PROCEDURES FOR THERMAL PERFORMANCE TESTING OF HOUSES

1.0 OBJECTIVES

This standard specifies a set of procedures that forms the basis of a test for newly constructed homes to determine the following parameters:

i) Conducting heat loss
ii) Ventilation heat loss
iii) Solar heat gain
iv) Appliance/people heat gain
v) Heating system performance

These values are to be used as inputs for a model to estimate the annual energy consumption of newly built houses.

A sub-objective of these tests is to provide immediate feedback to the builder in terms of direct measurements of construction quality.

2.0 TARGETS

This test is to be performed on newly constructed houses. It is undecided at this point whether testing will be done on all new housing, or whether quality control type spot checks will be done on each builder. The basic targets in the development of this procedure are as follows:

- The equipment and the test should require only one technician.

- The test period per house is limited to 24 hours.

- The procedure should produce repeatable results which will provide more accurate estimates of heat loss, heat gains and heating systems than do traditional, analytical techniques.

- It should be possible to conduct the test over a major portion of the year.

- Although the procedure presented is mainly directed at new homes having central, forced air heating systems, it should be flexible enough to accomodate other types of houses as well.

3.0 TESTING TECHNIQUES

There is no one, single test which can provide measurements of all the required parameters. However, there are a number of individual tests which, when grouped together to form a larger composite, could provide the necessary information. A list of such tests is as follows:

Parameter	Test
Heat Loss	Time Constant Electric Co-heat
Heating System Efficiency	Time Constant Electric Co-heat
Air Change	Tracer Gas
Air Tightness	Door Fan CGSB
Internal Gains	Electric Co-heat Time Constant
Solar Gains	Electric Co-heat Time Constant

As illustrated above, there are a total of four individual tests which can be integrated to form one larger test. Each of these tests are discussed below.

4.0 TIME CONSTANT

4.1 Equipment

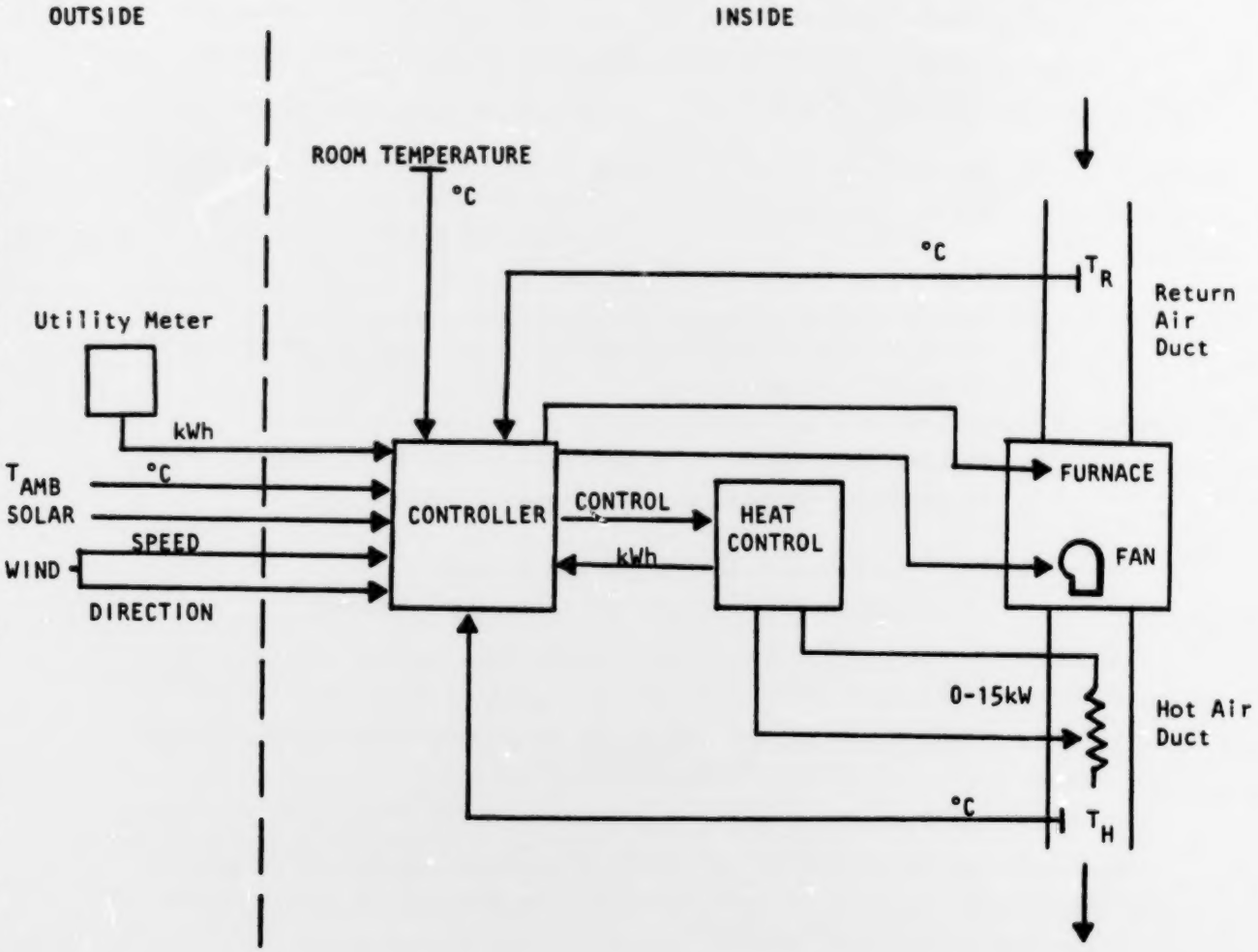
1. Two interior and one exterior temperature transmitter, each accurate to 0.1 K, from about -20°C to +60°C.
2. Three electric resistance heater elements, each rated at 5 kW.
3. Portable windspeed and wind direction indicator with digital output.
4. Portable pyranometer to measure solar radiation.
5. A kilowatt-hour transmitter to be connected to incoming service. The sensing device should generate and transmit a pulse train proportional to electrical energy consumption. This will be similar to a micromet kWh transmitter.
6. Sensing and recording of temperature, wind speed, wind direction and kWh is to be controlled by a microcomputer controller, possibly using a Zilog Z8 or MC6502 microprocessor as the control processing unit. This microcomputer will also be programmed to control the electric resistance heating elements.
7. Control signals initiated by the microcomputer controller will be received by a heating element controller. This controller will be designed to switch two fixed 5 kW resistive heating elements and one variable 5 kW element. The variable resistance will be controlled by SCR circuitry. The control sequence will allow for 0-15 kW variable hours. This heating element controller will be equipped with kWh metering devices capable of transmitting a digital signal or pulse train to the microcomputer controller.
8. Portable digital thermister, digital ammeter and other equipment required to calibrate instruments.

A block diagram illustrating the layout of this equipment is shown in Figure 1.

An alternative arrangement to electric resistance elements inserted in the hot air plenum would be a distributed network of resistance heaters placed throughout the house. This would allow for testing of the complete heating system, including the distribution ductwork. This alternative configuration may also require additional temperature sensors and solid state controllers. This may complicate the analysis, however, it will provide valuable information concerning the balancing and performance of the heating system.

FIGURE 1

TEST EQUIPMENT CONFIGURATION



4.2 Time Constant Test

1. Check time and program on data recorder and controller.
2. Chech house to ensure that all vents, doors and windows are closed. All ventilation fans such as kitchen and bathroom should be disconnected.
3. Measure ground temperature by measuring temperature of cold water from faucet.
4. Turn house thermostat to minimum setting.
5. Connect furnace control leads from programmer on to thermostat terminals inside furnace.
6. Run test program to ensure that it is operating properly in controlling furnace, fan and electric heater.
7. Run time constant test procedure program.
   This program will include the following sequence:

Time	Event
16:00 h	Stabilize the inside temperature of the house at approximately 23°C.
21:30 h	Start first stage with zero power input to resistance heaters. The furnace fan is to be operated continuously. This stage will continue for a period of 2½ hours or until sufficient data is obtained to determine the long time constant.
00:00 h	The second stage starts with 15 kW input to the resistance heaters. The furnace fan runs continuously. Heating continues for 2½ hours or until sufficient data is retrieved.
02:30 h	The third stage starts with 7.5 kW of power input to heaters. The furnace fan runs continuously. This stage also lasts for 2.5 hours or until sufficient data is retrieved.
05:00 h	The fourth stage starts with heat input from the furnace only. This stage lasts for 2.5 hours or until sufficient data is retrieved.
07:30 h	Heating is stopped and the house temperature is maintained at about 23°C until the technician arrives to remove the equipment.

During the course of the test, the following parameters are to be monitored:

T_{AMB} = Outside ambient temperature (°C)

T_t = Inside temperature to be measured on the main floor or a cold air return duct. (°C)

Q_E = Energy input into electric resistance heaters.(kWh)

Q_T = Total energy input to the house as measured by the utility meter.

W_S = Windspeed (m/s)

W_D = Wind Direction

These parameters should be measured in five minute intervals throughout the test.

The fuel consumption of the furnace will be determined by measuring the flow rate of the fuel with a test meter prior to testing and recording the furnace operation during the test.

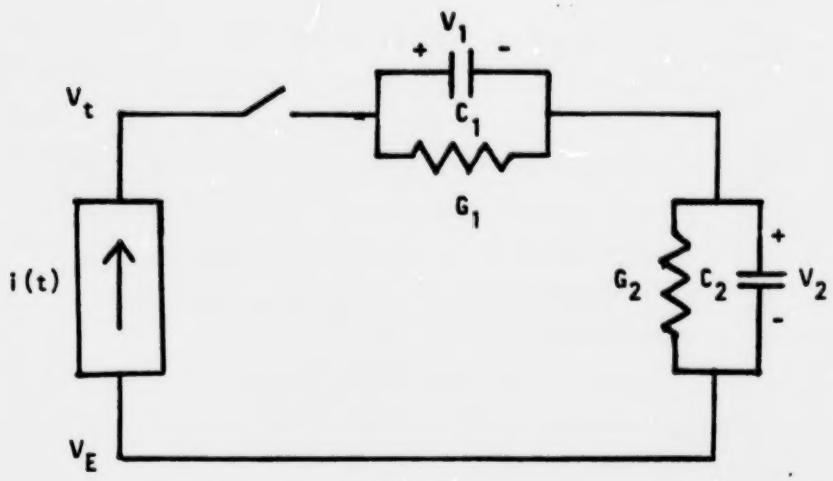
4.3 Analysis

The thermal time constant test is best described by using an electrical analogy. During the winter, houses are typically heated by a central, forced air furnace to maintain a constant indoor temperature. The energy required to do this is dependent on the thermal resistance and thermal capacity of the structure, as well as on the difference between inside and outside temperatures. In the electrical sense, this condition is similar to the resistance and capacitance in a circuit. The furnace is analogous to a current source in electronics, while temperature can be represented by voltage.

A simple electrical schematic for this circuit is shown in Figure 2. This electrical analogy models the performance with two lumped RC circuits in series. The first RC network, (symbolized by G_1 and C_1), has a short time constant to model heat transfer in the air contained in the house. The second

FIGURE 2

ELECTRIC CIRCUIT ANALOGY



Electrical

V_t = input voltage
V_1 = voltage across C_1
V_2 = voltage across C_2
i(t) = current source 0 or I
G_1 = conductance
C_1 = capacitance
G_2 = conductance
C_2 = capacitance
V_E = reference voltage

Thermal

T = inside air temperature
T_1 = temp. difference between air and structure
T_2 = temp. difference between structure and ambient
q(t) = heat source 0 or Q
G_1 = thermal conductance of air
C_1 = thermal capacitance of air
G_2 = thermal conductance of structure
C_2 = thermal capacitance of structure
T_E = equivalent outdoor temperature

$$\bar{E} = \frac{G_A T_A + G_B T_B}{G_A + G_B}$$

G_A = Above ground thermal conductance
G_B = Below ground thermal conductance
T_A = Air Temperature
T_B = Ground Temperature

Circuit G_2 and C_2 models the response of the thermal mass and the heat loss of the structure which possesses a significantly longer time constant than does the first network.

The response of this network to a constant current source is:

$$V_t(t) = V_1(o)e^{\frac{-G_1}{C_1}t} + \frac{i(t)}{G_1}(1 - e^{\frac{-C_1}{C_1}t}) + V_2(o)e^{\frac{-G_2}{C2}t} + \frac{i(t)}{G_2}(1 - e^{\frac{-G_2}{C_2}t}) + V_E$$

This is analogous to the thermal response:

$$T(t) = T_1(o)e^{\frac{-t}{t_1^*}} + \frac{q(t)}{U_1A_1}(1-e^{\frac{-t}{t_1^*}}) + T_2(o)e^{\frac{-t}{t_2^*}} + \frac{q(t)}{U_2A_2}(1-e^{\frac{-t}{t_2^*}}) + T_E$$

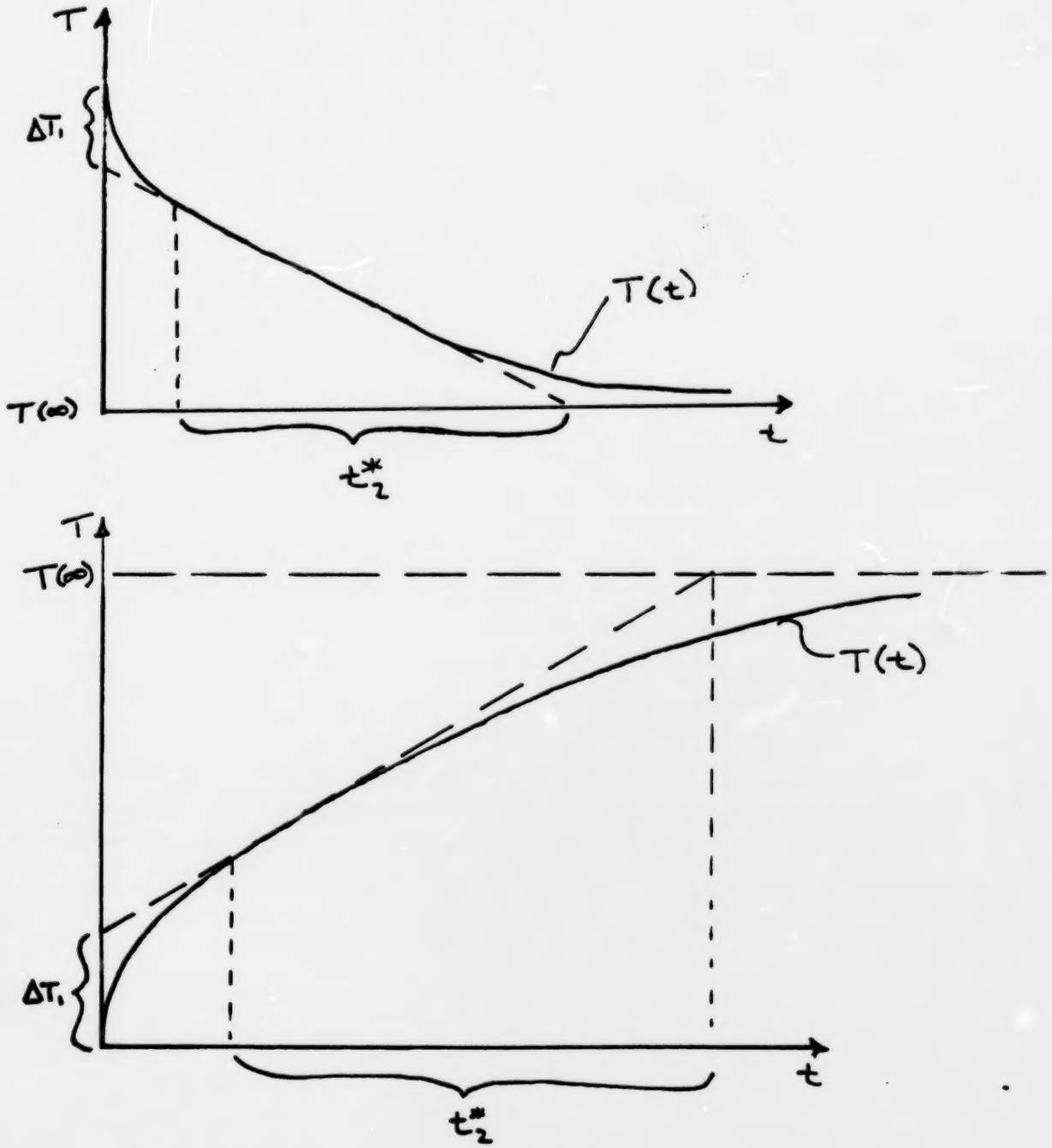
$$t_1^* = \text{time constant} = \frac{C_1}{G_1} \qquad t_2^* = \text{time constant} = \frac{C_2}{G_2}$$

It will be impossible to achieve zero heat input (Q=0) to the house, especially since the furnace fan must run continuously. As a result, there will be no ideal cooling curve and each response will have to be treated as a heating curve.

If t_1^* and t_2^* differ by a factor of 10 or more, they can be determined from experimental measurements. The time constant t_2^*, the conductance factor G and the equivalent outdoor temperature T_E can be determined by comparing the slopes of the three temperature responses resulting from different heat inputs.

Figure 3 illustrates two types of responses which may result during tests:

Figure 3



The slope, when measured at $t \gg t_1^*$, is defined by this function:

$$\text{Slope } (t) = \frac{T\ (\infty) - T\ (t)}{t_2^*}$$

where $T\ (\infty) = T_E + \frac{Q}{G_1} + \frac{Q}{G_2}$

Therefore:

$$T_E + \frac{Q}{G_1} + \frac{Q}{G_2} - \text{Slope } (t) \times t_2^* = T\ (t)$$

IF:

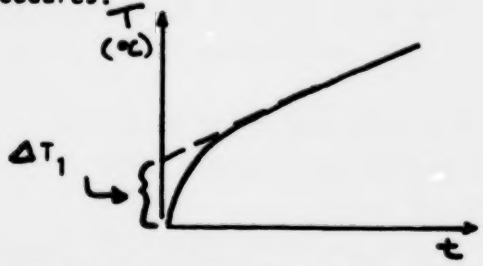
$\frac{1}{G_1} + \frac{1}{G_2}$ is replaced by R, the equation reduces to:

$$T_E + QR - \text{Slope } (t) \times t_2^* = T\ (t)$$

There are three unknowns; T_E, R, and t_2^*. Therefore, a minimum of three heating curves will be required and three equations will have to be solved simultaneously. The matrix representation would be:

$$\begin{bmatrix} 1 & Q_1 & \text{Slope 1} \\ 1 & Q_2 & \text{Slope 2} \\ 1 & Q_3 & \text{Slope 3} \end{bmatrix} \begin{bmatrix} T_E \\ R \\ t_2^* \end{bmatrix} = \begin{bmatrix} T\ (t)_1 \\ T\ (t)_2 \\ T\ (t)_3 \end{bmatrix}$$

G_1 can be solved by interpolating ΔT_1 from the slope as was proposed in the draft procedures.



However, since there will have to be heat input during the previous test, this ΔT_1 will be equal to $\frac{Q_n}{G_1} - \frac{Q_{n-1}}{G_1}$

Therefore: $G_1 = \frac{Q_n - Q_n{-1}}{T_1(\infty)}$

The steady state efficiency of the heating system can be determined using the fourth temperature response resulting from the operation of the furnace. In this case t_2^* and T_E will be known and the measured slope can be used to determine the $T_t(\infty)$ and Q_F as presented here:

$$T(\infty) = \text{slope } (+) \times t_2^* = T(t)$$

and

$$T(\infty) = T_E + Q_F R$$

therefore:

$$Q_F = \frac{T(\infty) - T_E}{R}$$

The efficiency of the system is then calculated as:

$$\text{Efficiency} = \frac{QF}{\text{Flow Rate and Heating Value}}$$

The flow rate is measured at the test meter and the utility billing meter.

5.0 ELECTRIC CO-HEATING (STEADY-STATE TEST)

5.1 Equipment

The equipment used for the electric co-heating test is the same as that used for the time constant test presented in Section 4.1.

5.2 Procedures

The preliminary procedures for the electric co-heating test are the same as those of the time constant test, listed in section 4.2, steps 1 through 6. The steady-state test procedures program will include the following sequence:

(a) The inside temperature should be stabilized at the same level as the existing thermostat controlling the furnace. This should be started at about 14:00 h.

(b) The microprocessor controller should be programmed to control the temperature within a span of 0.1°C of the setting by supplying constant energy through the electric resistance heaters inserted in the ductwork.

(c) The design heat loss of the house and the Δt at the time of testing should be used as a first approximation for the energy input to the heaters. The controller will be programmed to match the heat loss by increasing and decreasing the energy input to the variable heaters in increments less than 300 W at 5 to 10 minute intervals.

(d) This program should continue until 7:00 h. the next day. During the course of the test, the following parameters are to be monitored and recorded at 5 minute intervals:

Tamb - Outside ambient temperature (°C)

T_t - Inside temperature (°C)

Q_E - Energy input into electric resistance heaters (kWh)

Q_t - Total energy input to the house as measured by the utility meter

W_S - Windspeed (m/s)

W_D - Wind direction

5.3 Analysis

1. Calculate the average Tamb for the hours 18:00 to 06:00.

2. Estimate a value for the equivalent outside temperature T_E using the equation:

$$T_E = \frac{G_A T_A + G_B T_B}{G_A + G_B}$$

where:

T_A = the average value of Tamb

T_B = the estimated or measured ground temperature

G_A = the analytically derived heat loss factor for the portion of the envelope above grade

G_B = the analytically derived heat loss factor for the portion of the envelope below grade

3. Determine the average ΔT for the interval 0:00 to 06:00 h

$$\Delta T = T_A - T_E$$

4. Determine the average energy input to the house for the interval 0:00 to 06:00 h

5. The heat loss factor G_2 for the envelope is calculated as:

$$G_2 = \frac{Q \text{ avg.}}{\Delta T \text{ avg.}} \text{ (W/°C)}$$

6.0 HEATING SYSTEM EFFICIENCY

6.1 Equipment

For the heating system efficiency test, the equipment listed in Section 4.1 can be used. The essential components from that configuration of equipment are:

(a) A heater element control and metering device
(b) Hot air and return air duct thermocouples
(c) A data logger to record temperature readings
(d) A device capable of accurately measuring fuel flow to the furnace over short periods of time

6.2 Procedures

1. Turn on resistive heaters installed in hot air plenum; start with 5 kW load.
2. Ensure furnace fan is on continuous operation.
3. Monitor Δt between hot and cold air plenum. Allow approximately five minutes to reach steady state.
4. At steady state, record power demand in watts and Δt in °C.
5. Increase resistive load to 10 kW. Monitor and record Δt and watts as in 3 and 4.
6. Increase resistive load to 15 kW. Monitor and record Δt and watts as per 3 and 4.
7. Turn off resistive heat load.
8. Read fuel meter.
9. Turn on furnace.
10. Allow furnace to operate normally; maintain a constant temperature inside the house.
11. Measure Δt between the return air duct and hot air duct at 15 second intervals for a period of at least one hour.
12. Read fuel meter.

6.3 Analysis

1. Plot the measured Δt's as a function of input power as recorded in steps 3 to 6 in the procedures.

2. Calculate the slope of this line in °C/W. The calibration factor (C_F) for the furnace is:

$$C_F = \frac{1}{\text{Slope}}$$

3. Calculate the average ΔT from measurements taken during step 11.

4. Calculate efficiency of furnace (E_f) using the following equation:

$$E_f = \frac{\Delta T_{avg} \times C_F}{\text{FUEL} \times Q_{Fuel}}$$

where fuel consumption is measured in cubic metres or litres and Q_F is the heating value of the fuel in Watts/M^3 or Watts/l.

7.0 AIR CHANGE RATE

The tracer gas technique is recommended for determining air change rates and the resultant ventilation heat loss. There are numerous tracer gases such as Sulphur Hexaflouride, Ethane, Nitrous oxide, Propane, Carbon dioxide, and Perflourocarbon.

The air change should be monitored continuously during the test period with the controlled flow tracer gas technique. A tracer gas is injected into the house at a constant rate. The concentration is measured continuously in the return air duct using a Wilks Miran 101 infrared analyzer or a Photovac organic vapour analyzer, depending on the tracer gas. The volumetric air infiltration rate is calculated from the equation:

$$R = \frac{F}{C} - \frac{(dC/dt)\,V}{C}$$

where:

- R is the volumetric air infiltration rate (m^3/h)
- F is the flow of injected tracer gas (cc/h)
- C is the measured tracer gas concentration (ppm)
- dC/dt is the time derivative of the tracer gas concentration (ppm/h), averaged over at least 10 min.
- V is the volume of the house (m^3).

Mixing of the tracer gas is achieved by running the furnace fan continuously during the test period. All readings of tracer gas flow and concentration should be recorded by microprocessor for data analysis.

The use of a perflourocarbon tracer source as developed by the Brookhaven National Laboratory instead of a tracer gas could simplify the injection procedure. The tracer source is a flouroelastomer plug impregranted with a known mass of PFT and crimped with a metal shell. The PFT diffuses from the end of the plug at a known rate, typically between 0.5 to 5 nL/min. The detectability ranges from less than 0.01 pL up to 10,000 pL. The sources have useful lifetimes of from 5 to 10 years. Concentrations of the tracer are measured using a programmable absorption sampler known as a Brookhaven Atmospheric Tracer Sampler (BATS). Using this equipment to measure air changes is potentially less complicated and less expensive than using the traditional tracer gas technique.

Once the volumetric air change rate is known, the ventilation heat loss can be calculated:

$Q_L = pCR\Delta T$

p is the density of air (g/m^3)

C is the thermal capacity of air (W/g)

ΔT is the difference between outside and inside air temperature

Q_L is the ventilation heat loss in (W)

8.0 INTERNAL GAINS

The measurement of the internal heat gains can be accomplished using the electric co-heat equipment and procedures outlined in Section 5.0. The heat gain from specific appliances and/or people could be measured during the second half of the steady-state test. After the steady-state heat loss is determined, appliances in the dwelling can be manually operated for a specified period. The resultant load reduction of the electric heating system indicates the net heat gain to the house.

Internal gains could also be measured using the time constant test procedure. Once t^*_2, T_E, G_1 and G_2 are determined in the time constant test, the equipment can be programmed to operate through an additional cooling cycle with all the appliances on. When the slope of the cooling curve is measured at t = 2h, a revised equivalent outdoor temperature can be calculated, where:

$$T_E^1 = T(2.0) - \text{Slope} \times t^*_2$$

$$= T_E + \frac{Q}{G_1} + \frac{Q}{G_2}$$

therefore the heat gain from appliances (Q_A) can be calculated as:

$$Q_A = (T_E^1 - T_E)\ (G_1 + G_2)$$

In both the electric co-heat and time constant test the appliance gain Q_A can be compared to actual energy input measured by the utility meter to determine a heating efficiency.

9.0 SOLAR GAINS

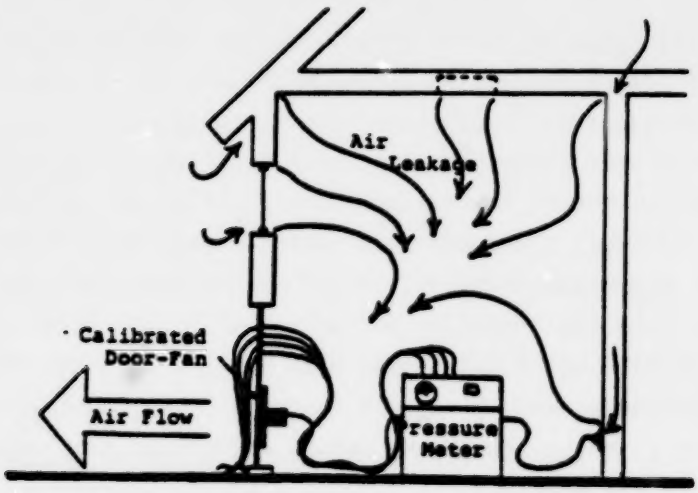
It may be possible to measu e solar gains using the electric co-heating or time constant technique. However, it would require testing the house for a period of several sunny days at different times during the heating season. The resultant solar heat gains measured, using the same electric co-heat or time constant test procedures as those for appliance heat gains, would have to be compared with the total solar energy available, and correlated with house orientation, in order to determine the annual gains.

10.0 AIR TIGHTNESS (DOOR FAN TEST)

The air tightness testing should be conducted according to the detailed draft CGSB Standard 149-GP-10M.

The test is designed to determine the effectiveness of the air/vapour barrier and the general tightness of construction associated with the design and installation of windows, doors, vapour barriers, exhaust ducts, chimneys, etc. The technician will use a portable door fan to test for air leakage rates and to assist in locating specific air leakage sites. The door fans are designed to induce negative pressures within the house and to measure the corresponding air flow. The operating principles of this test are illustrated below in Figure 4.

The presentation of test results will be expressed in terms of Equivalent Leakage Area (ELA), i.e., the size of the hole that would be created by gathering all leaks in the house into one place.



Air Tightness Test Apparatus

FIGURE 4

11.0 SUMMARY

The test/parameter matrix in Table 1 shows the suitability of each test procedure in determining the required performance parameter. The time constant test or electric co-heat test, combined with an air change test, could provide all the required measurements. In addition to the required parameters, the time constant test also provides a measurement of basement heat loss and thermal capacity. It has also been suggested that further study of the short time constant, which is determined predominantly by heat transfer through the air inside the house, could reveal a correlation with air change.

Despite its ability to measure these paramenters, there is very little working experience with time constant testing on houses, especially using the procedures presented here.

As with the experience with electric co-heat, tracer gas and door fan tests, there are a number of key factors which can introduce significant errors into the measurements of these test procedures. Specifically, they are:

(a) Wind speed
(b) Wind direction
(c) Outside ambient temperature
(d) Basement heat loss

The wind speed can affect conduction heat loss by changing the surface film coefficient. Wind can create various pressure profiles on the house and induce drafts in chimneys, flues and vents which change the ventilation rate and its associated heat loss.

The extent to which wind speed can affect film coefficients and ventilation rates is also dependent on wind direction in relation to house orientation and the location of chimneys, flues and vents, as well as the location of other major leaks in the envelope.

The magnitude of the difference between internal and external air temperatures can affect the air change rate through stack effect. Temperature and humidity can increase or decrease the air tightness of the structure, resulting in a decrease or increase in air change rates. The thermal conductivity in building materials can also change with temperature and humidity changes.

Basement heat loss is usually included as part of the total heat loss determined by these tests. However, the average ground temperature remains relatively constant throughout the heating season. If this fixed element of heat loss is not factored out, it can contribute significantly to the error of any spot measurement.

Previous experiments attempting to determine conductive heat loss factors using the steady state tests have resulted in variations of up to 30% in measured values of G on the same house. These variations can be attributed to the factors discussed here and the fact that the house is virtually never in a condition of steady state. Even though temperatures and wind speeds may remain constant during testing, the effects of changes in these parameters prior to testing must be considered, due to the long thermal response time of new houses. For example, if a new house has a time constant in the order of 20 hours, its response to any change in temperature will take almost 80 hours to reach a steady state condition. For this reason, ambient conditions will have to be closely measured before and during the test period. Correlation factors will have to be determined to allow these test measurements to be used to project annual heating requirements.

There is insufficient data available today to determine which testing procedures, Time-Constant or Electric Co-heating, are best. However, there is a great deal of similarity in the equipment and procedures required for each test. This will allow both procedures to be tested almost simultaneously on the same house. This type of testing on a selected number of new houses over a heating season will provide a valuable analysis of the test procedures in terms of accuracy, repeatability, and technical feasibility. It will also provide valuable data concerning the impact of uncontrolled variables on the accuracy of the results, and assist in developing the correlations required to project annual thermal performance.

TABLE 1

TEST PARAMETER MATRIX

	REQUIRED PARAMETER					OTHER PARAMETERS		
TEST	Conduction Loss	Ventilation Loss	Heating System Performance	Internal Gains	Solar Gains	Air Tightness	Basement Conduction Loss	Thermal Capacity
TIME CONSTANT	X	?	X	X	X	--	X	X
ELECTRIC CO-HEAT	X	--	X	X	X	--	?	--
AIR CHANGE	--	X	--	--	--	--	--	--
DOOR FAN	--	?	--	--	--	X	--	--

X - Parameter can be determined by proposed test method

-- - Parameter cannot be determined

? - Parameter can possibly be determined by proposed test method--field testing and data correlations are required